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MATHEMATICAL SUBSTANTIATION AND CREATION OF INFORMATION TOOLS FOR OPTIMAL CONTROL OF DRILLING AND BLASTING IN OPEN-PIT MINE

Purpose. To establish the rationale for the informational infrastructure necessary for effectively managing drilling and blasting operations in open-pit mining of rock deposits. To define the distribution function of natural rock blocks within the mass they comprise. To ensure timely access to data regarding the strength, fracturing characteristics of geological formations in their initial state, as well as the particle size distribution of mined materials obtained post-explosion.

Methodology. Statistical modeling techniques were employed to analyze the natural blockiness of rock masses. The approach involved utilizing the principle of measuring the dimensions of individual rock fragments through a transmitting television tube and differentiating the obtained results using electronic pulse circuits. Electronic circuits capable of implementing statistical dependencies derived for drilling machines and loading excavators were introduced.

Findings. Electronic devices have been proposed for real-time determination of the dimensions of natural rock blocks along their visible surfaces, as well as for assessing the strength, fracturing characteristics of rocks within the mass, and the particle size distribution of the mined material obtained during drilling and blasting operations.

Originality. The study has established the distribution function of natural rock fragments within a mass, serving as a prototype for the distribution function of visible rock fragments located on the sidewall of a slope. The theoretical developments of the proposed electronic devices are protected by patents.

Practical value. The presented tools for obtaining real-time, objective information about the natural blockiness, strength, and fracturing characteristics of rock formations in their initial state (before blasting), as well as relationship of these indicators with the particle size distribution of mined material obtained through blasting. These a tangible opportunity to implement optimal management of the entire blasting process, which will enable the enhancement of the technical and economic performance of open-pit mining

Keywords: *geological formations, drilling and blasting operations, mineral resources, particle size distribution, electronic devices*

Introduction. The development of open-pit rock mineral deposits involves the primary preparation of mining material through drilling and blasting operations. The quality of its fragmentation (particle size distribution) significantly affects the technical and economic indicators of the entire technological mining cycle [1]. Desired results in rock fragmentation can be realistically achieved if optimal parameters for blasting operations, based on corresponding research [2], are implemented under each set of mining-geological conditions. The concept proposed here considers rock fragmentation by explosion as a transitional process from one degree of fragmentation through natural and engineered cracks to a more intensive one, accomplished through the energy applied by the explosive material, as illustrated in Fig. 1.

From this diagram, it is evident that a crucial aspect of rock fragmentation is their blockiness, particularly the presence of "oversize" fragments, which are pieces that do not fit within the bucket of a loading excavator due to their size. In practice, the diameter of an oversize fragment (d_n) is determined by the formula

$$d_n = 0.8\sqrt[3]{V_k}, \tag{1}$$

where V_k is excavator bucket capacity, m^3.

The presence of "oversize" fragments in the mining material significantly reduces the productivity of loading and transportation equipment and necessitates the need for subsequent blasting [3].

As open-pit rock mineral deposits are progressively deeper, mining-geological conditions become more complex, leading to the requirement for a more pragmatic and economically justified approach to selecting the parameters for mass explosions.

Unsolved aspects of the problem. A known method for calculating the parameters of blasting operations, considering the particle size distribution of the mined material [4], lacks provisions for real-time quality control. Rational control parameters for blasting have been suggested to be determined based on computer modeling using a method for solving complex system analysis or synthesis problems [5]. However, applying such a model for optimization tasks is practically infeasible due to its high complexity and the multidimensionality of the involved variables.

The application of ultra-high-frequency (UHF) electric fields in conjunction with mechanical loading on rock during fragmentation is a promising approach [6], but it mainly pertains to the mining mass. Statistically justified is the feedback-based method for managing blasting operations, which involves selecting their parameters based on real-time information about the natural blockiness, strength, and fracturing of the rock before blasting, as well as adjusting the implemented parameters based on operational control data of the particle size distribution of the mined material under similar blasting conditions. In this context, it is worth noting the development and implementation of a device that allows the estimation of the relative strength of the rock based on the consumed energy during rotary drilling [7]. However, this information may not always be suitable, as it lacks direct measurements of rock strength and fracturing.

In scientific research, the typical approach for assessing the particle size distribution of mined material often involves the use of a photoplanimetric method. This method requires

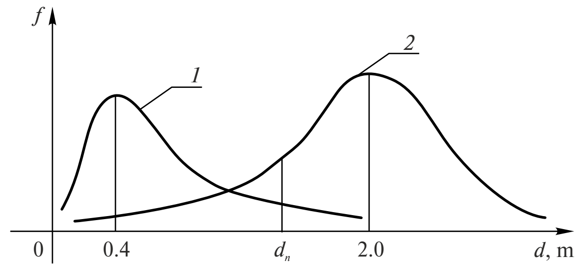

Fig. 1. Schematic representation of the distribution of mining mass fragments after blasting (1) and rock fragments within the mass before blasting (2):

d – average fragment diameter, m; d_n – diameter of non-standard fragment (oversize), m

capturing multiple photographs of the excavation surface and subsequently calculating the linear dimensions of fragments and their distribution within the plane of each photograph [8]. However, this method of data acquisition is quite labor-intensive, not always reliable, and can pose safety challenges.

An alternative automatic image processing approach has been proposed [9], which offers higher accuracy compared to manual counting. Nevertheless, it still requires capturing numerous high-quality photographs. Given these challenges, the goal is to provide real-time information about the initial state of the rock mass and its condition after blasting. The task involves developing electronic devices for the rapid determination of the natural blockiness of the rock, its strength, fracturing characteristics, and the particle size distribution of the mined material.

The purpose of this study is to mathematically substantiate and develop informational tools for the optimal management of blasting operations in quarries based on the particle size distribution of the mined material, with the incorporation of real-time quality control measures.

Methods. Statistical analyses were conducted on the results of selective measurements of the natural blockiness of granites extracted for gravel production. These measurements were compared to the theoretical distribution of rock mass fragments. To achieve this, a two-parameter function was employed

$$f(x) = e\alpha\left(\frac{x}{\beta}\right)^{\gamma} e^{-\left(\frac{x}{\beta}\right)^{\gamma}}, \qquad (2)$$

where α, β are distribution parameters; γ – standard multiplier.

Let us study this function to the extreme.

$$f'(x) = \frac{e\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\gamma} e^{-\left(\frac{x}{\beta}\right)^{\gamma}}\left[1-\left(\frac{x}{\beta}\right)^{\gamma}\right] \Rightarrow$$

$$\Rightarrow \begin{cases} \frac{e\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\gamma} e^{-\left(\frac{x}{\beta}\right)^{\gamma}} \neq 0 \\ 1-\left(\frac{x}{\beta}\right)^{\gamma} = 0 \end{cases} \Rightarrow x_{\max} = \beta; \quad f_{\max} = \alpha.$$

So, the parameters α and β correspond to the size and content of the predominant rock fragment in a specific volume of mining material, which is the mode and modal value of the function, respectively. Taking this into account, the distribution function of rock fragments or the function of its particle size distribution has the following form

$$f(x) = en\left(\frac{x}{x_{\max}}\right)^{\gamma} e^{-\left(\frac{x}{x_{\max}}\right)^{\gamma}}, \qquad (3)$$

where $n = f_{\max}$.

The presented function is of both theoretical and practical interest because its parameters facilitate unambiguous mathematical modeling and are utilized by technologists for the visual assessment of the homogeneity of a mass in its initial state and the degree of fragmentation achieved by blasting, thus evaluating the quality of the obtained mining material. The value of the normalizing factor γ is determined based on the condition

$$I = f(x) = en\int_0^{\infty}\left(\frac{x}{x_{\max}}\right)^{\gamma} e^{-\left(\frac{x}{x_{\max}}\right)^{\gamma}} dx = 1.$$

According to [10], we have $I = \frac{enx_{\max}}{\gamma}\Gamma\left(\frac{\gamma+1}{\gamma}\right)$, where $\Gamma\left(\frac{\gamma+1}{\gamma}\right)$ – Euler's gamma function $\Gamma(\alpha) = \int_0^{\infty} x^{a-1}e^{-x}dx.$

Practically, $\Gamma(a) = (a-1)\Gamma(a-1)$, and if α is a positive integer, then $\Gamma(a) = a!$, in a specific case $\Gamma(1) = 1$.

The statistical distribution of natural blocks along the sidewall of the slope, measured under industrial conditions, was compared to their theoretical distribution calculated using formula (3). In this case, the parameters of the function corresponded to the size and content of the predominant fragment in their static distribution. The obtained results are presented in Table 1.

As evident from this table, the modeling error of the particle size distribution using the proposed function does not exceed the dominant error in similar calculations.

In general, there are no methods for the exact measurement of the linear dimensions of all fragments in the mass they constitute at present. Obtaining a 100 % standard is not feasible. Furthermore, any studies on the natural blockiness of a slope are conducted on its visible portion, which is further fragmented by previous blasting. Therefore, measurement results need to be adjusted in the direction of increasing them, which, in turn, necessitates research on creating a distribution function for natural blocks.

Let x be a continuous random variable with a known probability density function $f(x)$. Then the probability density function $f(y)$ of the random variable y is determined by the following expression [10]

$$f(y) = f_x(\varphi^{-1}(y))\frac{d\varphi^{-1}}{dy}, \qquad (4)$$

where $\varphi(x)$ is a continuously differentiable, increasing function whose domain coincides with the range of the random variable x; $\varphi^{-1}(y)$ is inverse function.

Table 1

Comparative Data of Experimental and Theoretical Studies on the Distribution of Natural Blocks in Granite Quarries

Size interval, m x_i; x_{i+1}	0; 0.6	0.6; 1.2	1.2; 1.8	1.8; 2.4	2.4; 3.0	3.0; 3.6	3.6; 4.2	4.2; 4.8	4.8; 5.4
Mean values, $\bar{x}_i$	0.3	0.9	1.5	2.1	2.7	3.3	3.9	4.5	5.1
Variants, n_i	83	470	552	497	360	193	110	28	7
Relative frequencies, w_i	0.06	0.34	0.4	0.36	0.26	1.14	0.08	0.021	0.003
Value $f(x)$: $x_{\max} = 1.5$; $n = 0.4$; $\gamma = 1.47$	0.09	0.32	0.4	0.35	0.24	0.14	0.07	0.04	0.01

Table 2

Values of the distribution function of natural blockiness in the granite mass

Size interval, m y_i; y_{i+1}	0; 0.6	0.6; 1.2	1.2; 1.8	1.8; 2.4	2.4; 3.0	3.0; 3.6	3.6; 4.2	4.2; 4.8	4.8; 5.4
Mean values, $\overline{y}_i$	0.3	0.9	1.5	2.1	2.7	3.3	3.9	4.5	5.1
Value $f(y)$ $x_{max} = 1.5$; $n = 0.4$; $\gamma = 1.47$	0.06	0.23	0.33	0.32	0.27	0.20	0.12	0.08	0.05

Given that the particle size distribution of the natural blockiness of the mass is subjectively assessed based on measurements taken along the slope and accordingly supplemented, we represent the function $f(y)$ as a transformation of (3) using the function $y = \varphi(x)$ [11].

The investigation of the statistical dependence of the natural blockiness of the mass on the particle size distribution of rock fragments located on its visible surface, i.e., finding the function y, was conducted using a specially developed device [2, 12]. On its diagram, designed in the form of a circle, pressure drops in the hydraulic system of the rotary drilling machine were continuously recorded, which occur when its cutting bit passes through cracks.

As a result of the correlation analysis of the research findings, it was established that the mentioned function has the following form

$$y = 1.2x. \tag{5}$$

Finally, considering (3, 4 and 5), the following function for the distribution of natural blockiness in the rock mass was obtained [13]

$$f(y) = \frac{en}{1.2}\left(\frac{y}{1.2x_{max}}\right)^{\gamma} e^{-\left(\frac{x}{1.2x_{max}}\right)^{\gamma}}. \tag{6}$$

For the conditions in Table 1, when $\overline{y}_i = \overline{x}_i$, the computed values of this function are provided in Table 2.

The graphs constructed based on the data from Tables 1 and 2 are shown in Fig. 2.

Comparing the graphs in this figure, it is important to note a reduction in conditioned fragments and a significant increase in non-conditioned fragments (oversize) of granite deeper into its mass. Consequently, the evaluation of the natural blockiness of the rock mass using formula (6) plays a dominant role in the design of mass blasting [14].

Results and discussion. An automatic device has been developed for the real-time determination of the distribution of visible rock fragments on the slopes. This device utilizes the principle of measuring their dimensions with a beam from a transmitting television tube and differentiating the obtained results with an electronic pulse circuit. The block diagram of the device is shown in Fig. 3.

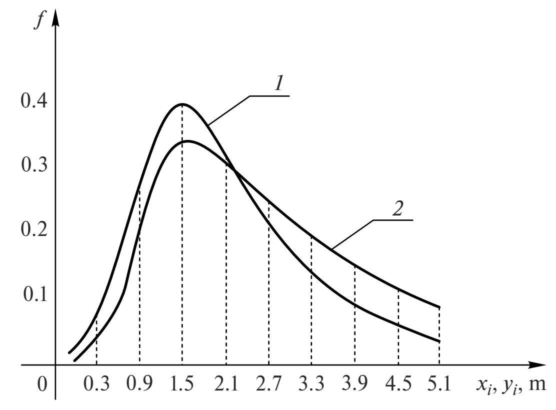

Fig. 2. Graphs of the distribution of natural granite blocks based on the data from Tables 1 and 2:

1 – curve of the distribution of granite fragments along the slope (function f(x)); 2 – curve of the distribution of granite fragments in the mass (function f(y))

The provided block diagram includes a reading block *1*, a square pulse generator *2*, electronic switches *3, 4, 5,* an anti-aliasing circuit *6*, a generator *7*, delay lines *8*, power amplifiers *9*, waiting multivibrators (formers) *10*, trigger devices *11* and counting devices *12*.

The operation of the device is based on simulating an electronic beam block that reads with varying illumination of rock fragments and intervals between them. A transmitting television tube, a synchronization and deflection unit of a television set are used as the reading block.

The basic electrical circuit of the device is shown in Fig. 4.

It operates as follows: The image of the object under investigation is projected onto the photocathode of the transmitting tube. An electronic beam of the tube is simulated by a square pulse generator, which uses a symmetrical multivibrator assembled on transistors *13, 14.* The rectangular pulses of the generator, passing through a phase-inverting stage on transistor *15*, are amplified by a two-stage power amplifier, assembled on transistors *16, 17.* Its load is the deflection coils *18, 19* of the transmitting tube. Due to the deflection of the electronic beam of the tube with square pulses, the image of the investigated object is traced by two parallel dashed lines. Depending on the brightness of the read area, the voltage on the load of the transmitting tube changes.

The square pulse generator controls electronic switches via an emitter repeater on transistor *20,* assembled with transistors *21–24.* Using electronic switches, information from the upper and lower dashed rows of each tracing is sent to an independent channel for further processing. Since the brightness of the plane is much higher than the brightness of the intervals between them, when the upper dashed line passes through the interval between the fragments and the lower one passes through the plane of the fragment, the trigger device, transistors *25–27*, forms a pulse corresponding to the first (initial) tracing of the entire fragment. When the lower dashed line passes through the interval between the fragments and the upper one passes through the plane of the fragment, the trigger device, transistors *28–30*, forms a pulse corresponding to the last tracing by electronic beams of a separate rock fragment. The pulses corresponding to the first and last tracings of each fragment are distributed in time in proportion to the linear size of the fragment. The threshold for triggering the trigger devices is chosen

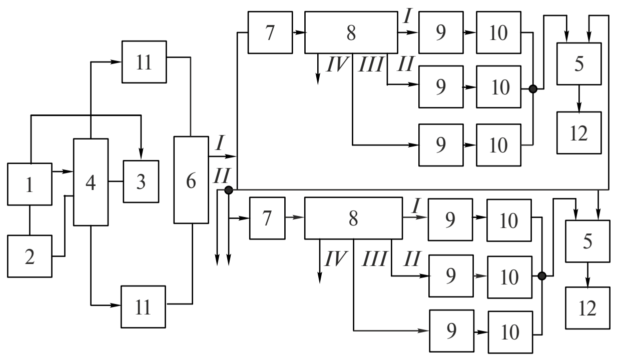

Fig. 3. Block diagram of the device for real-time determination of the dimensions of visible rock fragments

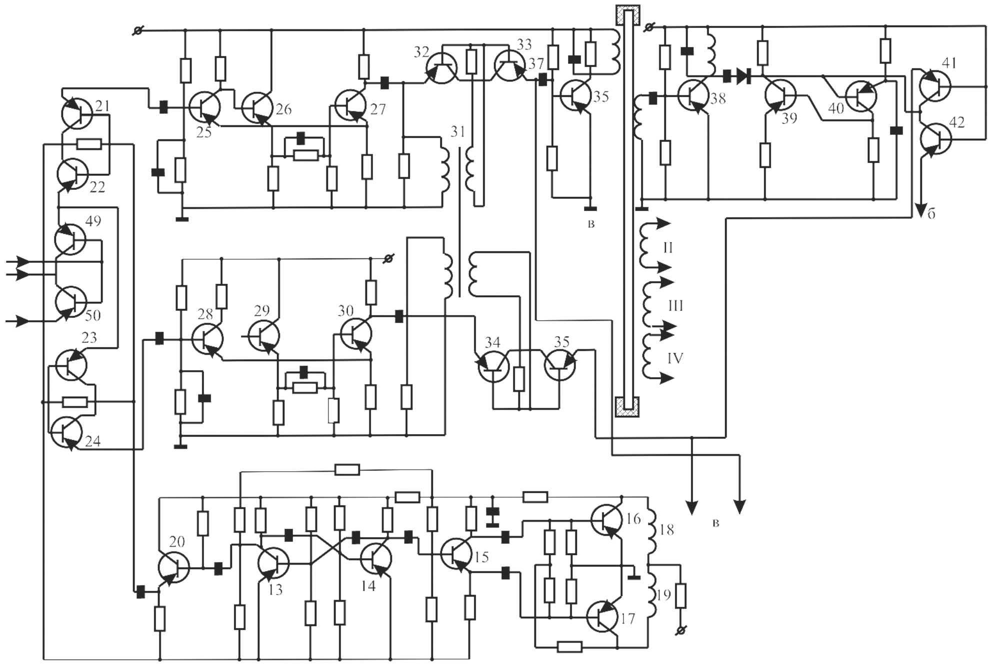

Fig. 4. Schematic diagram of the device for real-time determination of the size of visible rock pieces

to eliminate the influence of unevenness in the brightness of the fragment surfaces on the accuracy of the results.

The pulses generated by the triggering devices enter the anti-aliasing circuit, consisting of transformer *31* and electronic switches on transistors *32–34*. The anti-aliasing circuit prevents the appearance of a signal at both outputs simultaneously when the electronic beam of the transmitting tube traces areas with the same illumination. The pulse corresponding to the first tracing of the fragment, through the electronic switch (*32, 33*), in each channel, enters the input of the shock excitation contour generator, assembled on transistor *36*. The generator emits several high-frequency oscillations that propagate along the delay line. The magnetostrictive delay line has several output windings arranged so that the pulse of the first tracing of the fragment appears at output I after a time proportional to the minimum size of the fragment of this counting channel. Continuing to propagate along the delay line, the pulse appears at its subsequent outputs II, III, IV, respectively, with time intervals corresponding to the tracing of one row. From the output of each winding of the delay line, the signal enters the corresponding power amplifier *9* (Fig. 2), and for the first counting channel, the amplifier is assembled on transistor *38*. This signal also goes to the generator – multivibrator *10* (Fig. 3), assembled on transistors *39, 40*. The multivibrator generates a square pulse and applies it to electronic switch *5* (Fig. 3), assembled on transistors *41, 42*. The switch receives an impulse through transistors *34, 35*, which corresponds to the last tracing of the same fragment.

The pulse of the last tracing of each piece arrives simultaneously at the electronic switches of all counting channels. In the counting channel where there is a time coincidence between the pulses of the first and subsequent tracings of an individual piece, an impulse is issued to the tallying device *12* (Fig. 2), where the sum of pieces (of that channel) is increased by one. The tallying device is a high-speed pulse counter with tallying sections. The number of counting channels is selected depending on the required quality of particle size analysis. The device can operate in both continuous reading and standby modes. This is achieved by using a synchronization block, as shown in Fig. 5.

This block consists of a trigger using transistors *43* and *44*, an amplifier using transistor *45*, and a multivibrator using transistors *46* and *47*. In standby mode, switch *48* is set to the far left position. The trigger is flipped by the frame blanking pulse of the transmitting tube deflection system and triggers the waiting multivibrator. The multivibrator outputs a square pulse with a duration equal to the duration of one frame, opening the electronic switch on transistors *49* and *50* (Fig. 5). To read again, you need to press button *51* (Fig. 5). In continuous reading mode, switch *48* (Fig. 5) is set to the far right position, and the frame blanking pulse passes through amplifier *45* to the waiting multivibrator, which opens the electronic switch on transistors *49* and *50* for each frame reading. The presented device allows reading only visible pieces of rock mass, so the results of their measurements will have some errors.

The next important characteristic of rock fragmentation by blasting is its strength and fracturing within the mass. Based on selective statistical studies, it has been established that the strength of the rock correlates with the drilling speed of the drilling machine under fixed operating conditions, i. e. [16]

$$f = K\sqrt[4]{pnt^2}, \tag{7}$$

where p is pressure in the working hydraulic cylinder of the drilling rig (axial force), in atm; n: rotational speed of the drilling rod, (rev/min); t: time taken to drill a specific length of the borehole, (min).

The device described above implements an algorithm for calculating the rock strength coefficient based on the conversion of the controlled parameters *p, n* and *t* into proportional electrical signals. Additionally, it performs the counting of cracks intersected by the rotary drilling bit. The block diagram of this device is depicted in Fig. 6.

The device operates based on the time-pulse conversion of the main parameters of the controlled drilling process section,

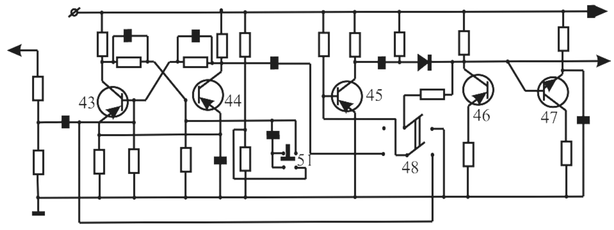

Fig. 5. Schematic diagram of the synchronization unit

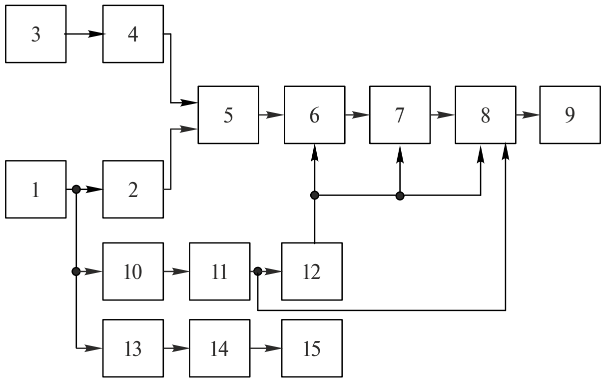

Fig. 6. Block diagram of the device for measuring the strength and fissuring of rocks during drilling

followed by processing the obtained values according to the given algorithm. The voltage proportional to the axial force on the rod is taken from sensor *1* and fed to the input of voltage-to-frequency converter *2*. The rotation speed of the drill rod is monitored by sensor *3*, and its voltage is input into voltage-to-frequency converter *4*. The pulses from converters *2* and *4* are sent to the input of summator *5*, where they are summed up. Thus, during the drilling of the investigated section of the well over time, block *5* provides a number of pulses at its output, proportional to the average strength of the rock in that section.

The pulses from the summator are then sent to the input of frequency divider 6, where they are divided into a convenient number for further processing. For measurements in a 1-meter section of the well, the calculation coefficient is taken as 128. This value is determined by the range of parameters and the output voltage characteristics of the applied sensors *1* and *3*, as well as the voltage-frequency characteristics of converters *2* and *4*. After the frequency divider *6*, the pulses go to the input of block *7*, which distributes the pulses into intervals. A total of five intervals are specified, into which the total number of pulses coming to the input of block *7* is divided. This takes into account the peculiarities of rock destruction during blasting. It is known that control of the drilling and blasting operations complex using real-time information about rock properties that determine their strength can be effectively carried out in cases where $12 \le f \le 22$. The specified range of changes in the strength coefficient is accepted for more accurate measurement in the five following intervals: 12–14, 14–16, 16–18, 18–20, 20–22. The number of measurement intervals determines the number of intervals into which the total number of pulses is divided. Given that the dependence of the rock strength coefficient on drilling process parameters is nonlinear, the number of pulses in the intervals varies. This is determined using block *7* based on formula (7).

From the output of block *7*, the pulses are input into a decoder, where they accumulate over the drilling time of the controlled well section and are decoded for communication with block *9* for strength indication.

The voltage taken from sensor *1*, representing axial force, is also sent to the input of control pulse generator *10*. It produces a control pulse, where the leading edge corresponds to the beginning of drilling the investigated well section, and the trailing edge corresponds to the end. On the trailing edge of the control pulse, pulse generator *11* produces a readout pulse, which is input into the enable of decoder *8*. When this pulse is present, information stored in the decoder is read, and a control signal for the digital indicators of block *9*, displaying the strength coefficient values, is generated. The readout pulse is also sent to the input of pulse generator *12*, which generates a reset pulse, clearing the memory elements of blocks *6, 7* and *8*. When this pulse is applied, the device is prepared for measuring the strength of rock on the next well section.

The cracking of drilled rocks is recorded as follows: the voltage from sensor *1*, measuring the force, is sent to the input of pulse generator *13*. During a short-term pressure drop in the hydraulic system of the drilling machine, which corresponds to the moment of intersecting a crack by the rock bit, generator *13* produces a pulse corresponding to this pressure drop. These pulses from generator *13* are input into block *14*, which counts their quantity over the drilling time and controls digital indicators *15* of the crack block. The number of pulses registered by this block corresponds to the number of cracks in the measured well section [17].

The resetting of indicator readings is done manually after reading the measurement results. The device allows for measuring the strength and cracking of rocks on well sections of *1* and *8* meters in length, with the latter corresponding to the length of a single rod. The basic electrical scheme of block *7* for distributing pulses across intervals is shown in Fig. 7. It consists of triggers (T1–T5) connected in a binary frequency division scheme and logic elements "AND".

This is the main functional block of the device where the frequency division coefficient of the pulses into intervals is changed according to equation (7). Extensive statistical studies on the main parameters of rock bit machine operation on rocks of varying strength were carried out at the selected length of the well section and specified frequencies of converters *2* and *4* (voltage-frequency). As a result, the total number of pulses entering the frequency divider *6* was determined. Taking into account the adopted division coefficient (128 for a 1-meter well section), the correspondence of the number of pulses entering decoder *8* to the rock strength value was established [18]. The obtained data are presented in Table 3, which was compiled based on the methodologies provided in [2].

These automatic devices provide operational information about rock fragmentation, its strength, and cracking. This information characterizes the initial state of the controlled object. To assess the effectiveness of the applied parameters of blasting operations as a method of control, it is necessary to have objective information about the quality of rock fragmentation obtained after the explosion. Since the contrast between individual rock pieces on its surface is obscured, obtaining information about the final state of the object by shooting such a surface has significant errors [19].

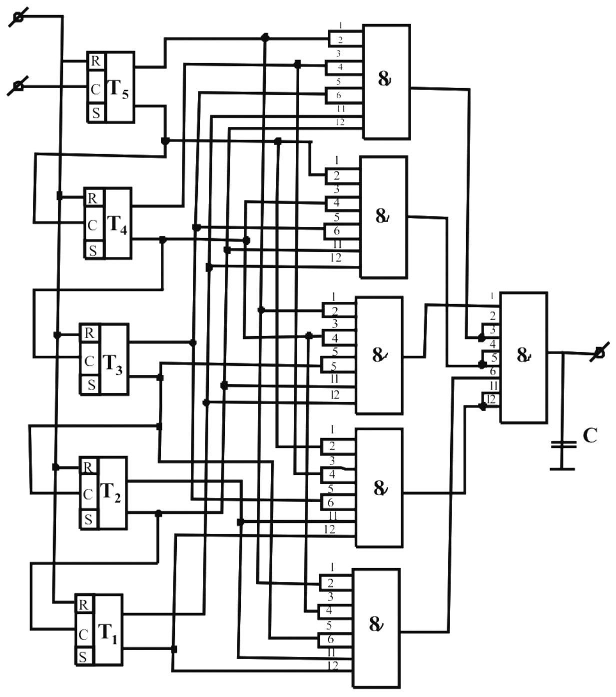

Fig. 7. Block diagram of the pulse distribution across intervals

Table 3

Distribution of the total number of pulses across intervals during drilling a well on a 1-meter section

Strength coefficient	Axial force, atm	Boom rotation speed, rpm	Drilling time, min	the number of pulses that come to the input	
				frequency divider	decoder
14	60	105	4.9	1,024	8
		100	5.1	1,030	8
	65	100	4.7	890	7
		95	4.8	920	7
16	65	95	6.5	1,354	11
		90	6.7	1,359	11
	70	90	6.0	1,285	10
		85	6.3	1,305	10
18	70	85	9.6	1,742	14
		80	9.8	1,744	14
	75	80	8.9	1,652	13
		75	9.4	1,680	13
20	75	75	10.6	2,293	18
		70	10.8	2,312	18
	85	75	10.2	2,153	17
		70	10.5	2,204	17
22	85	70	13.0	2,924	23
		65	13.3	2,962	23
	95	70	12.4	2,764	22
		65	12.6	2,793	22

Statistical studies were conducted on the operation of excavators of the EKG-4,6 and EKG-8I types under different load conditions of mining materials with various particle size distributions. The characteristic oscillograms of the observations are shown in Fig. 8.

From this Figure, it can be observed that the energy consumption for loading mining materials of different fragmentation quality statistically differs significantly because the durations of excavation cycle elements vary considerably, as shown in Table 4.

The data in this table, however, indicate that the main characteristics of excavator operation can be effectively used to assess the particle size distribution of mining materials [20].

An automatic device has been developed for real-time determination of the particle size distribution of mining materials during excavation. It is based on the statistical relationship between the total loads of the lifting drives and the pressure of the excavator with the quality of fragmentation of the rock mass. Its block diagram is shown in Fig. 9.

The device operates based on the principle of time-pulse conversion of the input signal. The voltage, which is taken from the shunts of the lifting and pressure drive of the excavator, is fed to the input of the voltage-to-frequency converter *1* and *2*. The frequency of pulses from their outputs, proportional to the input voltages, is fed to the input of the summer *3*, where they are summed. The total frequency from output *3* is applied to the input of the electronic switch *4*, which opens only during the process of scooping up the mining material. The voltage taken from the shunt of the lifting drive is also fed to the input of the generator *6*, which generates a control square pulse, where the leading edge corresponds to the beginning of scooping up the mining material and the trailing edge corresponds to the end. The threshold level at which *6* operates is chosen to exclude the analysis of unproductive cycles (planning the bottom of the recess, discarding non-conforming pieces, etc.).

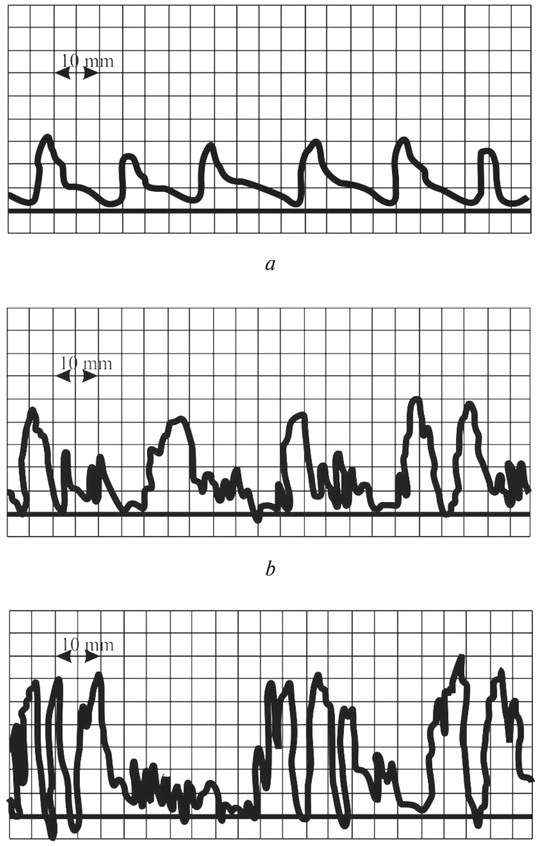

Fig. 8. Oscillograms of the mining process for mining materials with specified average fragment diameter, mm:
a – 320; b – 512; c – 670

Table 4

Parameters of the excavation cycle for mining materials with different particle size distributions

Diameter of the average piece, mm		320	512	670
Output of substandard pieces, %		0	1.2	5.0
Excavation cycle duration, s	Maximum	44.0	57.0	70.0
	Average	33.7	39.0	43.2
Duration of rock mass extraction, s	Maximum	11.4	15.1	19.3
	Average	6.1	9.9	12.8

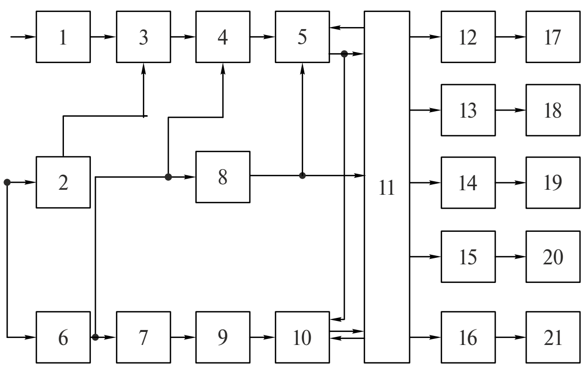

Fig. 9. Block diagram of the device for real-time monitoring of particle size distribution of mining materials during excavation

From the output of *6*, the control pulse is applied to the input of *4*, as well as to the input of the reset pulse generator *8* and the time delay element *7*. When the control pulse arrives at the input of the electronic switch *4*, it opens, and the total frequency of pulses from its output is applied to the input of the frequency divider *5*, which is designed to divide the number of incoming pulses over the duration of scooping into five intervals. The division coefficients for the intervals are different and are as follows: 1021, 1024, 992, 944, 896.

From the output of *5*, the pulses are applied to the input of the decoder *11*, where they are stored until the end of the scooping process.

The control pulse from the output *6* is applied to the input of the time element *7*, where the leading edge is delayed by 3–3.5 seconds. This allows excluding the analysis of load pulses caused by sharp controller command switching or rapid bucket movement on the mining material surface. From the output *7*, the pulse is applied to the input of the readout pulse generator *9*, which, on the trailing edge of the control pulse, generates a readout pulse that enters the decoder via the overload limit *10*. The overload limit *10* excludes the analysis of excavator drive loads with values and durations greater than the load generated when scooping up the maximum-sized piece (801–1000 mm). Such conditions may occur, for example, when the drives are locked or due to the "failures" of certain charges [21].

When the readout pulse arrives at the input of the decoder *11*, the information recorded there is analyzed. From the decoder's output, depending on the magnitude and duration of the load during scooping, the pulse is sent to the corresponding counting channel, where, after amplification by amplifiers *12, 13, 14, 15, 16*, it is registered by the respective counters *17, 18, 19, 20, 21*.

From the output *6*, the control pulse is applied to the input of the reset pulse generator *8*, which generates a reset pulse on the trailing edge that enters inputs *5* and *11*. The reset pulse is applied after the readout pulse and prepares the device for the analysis of the next excavation cycle. The operation of the device during the analysis of subsequent excavation cycles is similar to the one described.

Conclusions. The proposal suggests considering the fragmentation of rocky formations through blasting as a transitional process from one degree of fragmentation, primarily driven by natural and technical factors, to a more intensive degree due to the energy released by explosive materials.

The effectiveness of applying feedback control methods for blasting operations is highlighted, where the selection of their parameters is based on objective information about the rock's blockiness, its strength, and its susceptibility to cracking before the explosion. It also involves adjusting the implemented parameters based on real-time data regarding the granulometric composition of the mined material, in case of similar blasting conditions.

An automatic device has been developed to provide real-time assessment of the distribution of rock fragments. This device employs the principle of measuring their sizes using a transmitting television tube and further differentiation of the obtained results through an electronic pulse circuit.

Satisfactory results have been obtained by comparing the statistical distribution of visible natural blocks, measured under industrial conditions, with their theoretical distribution based on the proposed function.

A statistical function for the natural blockiness within the rock mass has been established and practically tested.

Additionally, an automatic device for measuring the strength and crack susceptibility of rocks during drilling has been developed. It implements a statistically determined relationship between the strength coefficient and the parameters of the drilling machine's operation, and it also calculates the number of cracks intersected by the drill bit.

Furthermore, an automatic device has been designed for the real-time determination of the granulometric composition of the mining mass during excavation. This device is based on the statistical dependence between the total load on the lifting and thrust mechanisms of the excavator and the quality of rock fragmentation due to blasting.

These methods and technical tools for obtaining objective information about the state of rocky formations before and after blasting offer practical applications in mining operations, particularly in the optimal management of drilling and blasting activities.

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Математичне обґрунтування та створення інформаційних засобів оптимального керування буропідривними роботами на кар'єрах

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Мета. Обґрунтування розробки інформаційного забезпечення, необхідного для оптимального управління буро-вибуховими роботами при відкритій розробці родовищ скельових корисних копалин. Встановлення функції розподілу природних блоків породи в масиві, який вони складають. Оперативне забезпечення даних про міцність і тріщинуватість гірничих порід у початковому їх стані та гранулометричний склад гірничої маси, одержаної після вибуху.

Методика. Застосовані методи статистичного моделювання природної блочності масиву скельових гірничих порід. Запропоновано використовувати принцип зчитування розмірів окремих шматків породи променем передаючої телевізійної трубки та диференціювання одержаних результатів електронно-імпульсною схемою. Упроваджені електроні схеми, що здатні реалізовувати статистичні залежності, отримані для бурових верстатів і навантажувальних екскаваторів.

Результати. Запропоновані електронні пристрої для оперативного визначення розмірів природних блоків порід по видимій площині кожного, міцності та тріщинуватості порід у середині масиву та гранулометричного складу гірничої маси, одержаної у процесі проведення буровибухових робіт.

Наукова новизна. Встановлена функція розподілу природних шматків породи в масиві як прообраз функції розподілу видимих шматків породи, розташованих на боковій поверхні уступу. Теоретичні розробки приведених електронних пристроїв захищені авторськими свідоцтвами.

Практична значимість. Представлені засоби оперативного отримання об'єктивної інформації про природну блочність, міцність і тріщинуватість порід у початковому їх стані (до підриву) та зв'язок цих показників із гранулометричним складом гірничої маси, одержаної в результаті вибуху. Ці дані відкривають реальну можливість упровадження оптимального управління комплексом буро-вибухових робіт, що дозволить підвищити техніко-економічні показники відкритого добування скельових корисних копалин.

Ключові слова: *гірничі породи, буро-вибухові роботи, корисні копалини, гранулометричний склад, електронні пристрої*

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